

Received August 25, 2020, accepted September 10, 2020, date of publication September 22, 2020,  
date of current version November 17, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3025812

# 3D Fragmentation Metric and RCSA Scheme for Space Division Multiplexing Elastic Optical Networks

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This work was supported in part by the National Key Research and Development Program of China under Grant 2018YFF0301004, in part by the National Natural Science Foundation of China under Grant 61905060, and in part by the Natural Science Foundation of Hebei Province under Grant F2019402240 and Grant F2018402198.

**ABSTRACT** The space division multiplexing elastic optical networks (SDM-EONs) based on multi-core fiber (MCF) are an effective solution to improve transmission capacity. In SDM-EONs, spectrum resources take on three-dimensional (3D) properties (i.e., frequency, time, and space), which brings new spatial constraints to network resource allocation. Meanwhile, the spectrum fragmentation in the network also presents same characteristics with the setup and release of dynamic lightpath. To improve the success rate of transmission and the utilization of network resources, it is necessary to evaluate network fragmentation effectively from the three dimension. Therefore, this paper focuses on a new fragmentation measurement for SDM-EONs. Firstly, the 3D fragmentation metric is carried out considering the frequency-time-space domain. Then, routing, core, and spectrum allocation (RCSA) scheme is proposed to allocate the spectrum resource with minimal future fragmentation and core resource with maximal free resource reservation. Simulation results show the proposed scheme better in blocking probability, spectrum utilization, and fragmentation rate.

**INDEX TERMS** Fragmentation metric, RCSA, SDM, three-dimensional properties.

## I. INTRODUCTION

Many high-traffic applications have emerged over the Internet with the rapid development of big data, cloud computing, and 5G mobile communication. These applications require huge bandwidth support [1], and optical networks, as the main carrier mode of the transport layer, face great challenges. Traditional fixed wavelength division multiplexing networks result in a waste of spectrum resources. To meet the needs of Internet and communications in the future, elastic optical networks (EONs) with greater flexibility and scalability [2], [3] were proposed. Compared with traditional transmission mode, the advantage of EONs lies in the flexibility of resource allocation, which makes a reasonable spectrum planning the focus. Routing and spectrum allocation (RSA) schemes are the fundamental technology of resource planning [4].

The associate editor coordinating the review of this manuscript and approving it for publication was Qunbi Zhuge <sup>1</sup>.

In EONs, a large number of requests are generated randomly in time, and when dynamic RSA is carried out for them, three constraints (i.e., spectrum continuity, contiguity, and non-overlapping) need to be satisfied. Therefore, the setup and release of dynamic lightpath will inevitably create gaps (i.e., discontinuous resources) in the optical spectrum. Considering spectrum continuity and contiguous limitations, the resources are difficult to be utilized by subsequent requests, whereas new discontinuous resources constantly generate, resulting in higher blocking probability and lower spectrum utilization. The resources are known as spectrum fragmentation, which severely affects network performance [5]. In essence, effectively solving the fragmentation problem is a necessary means to improve network performance.

In order to address the fragmentation problem for EONs, two main methods have been adopted: reactive and proactive. Reactive solutions use defragmentation, which is the process of removal of fragmentation by rearranging already

established connections [6]. However, defragmentation will consume a large amount of cost and time. More works tend to prevent fragmentation before its emergence (i.e., proactive solutions) [7], [8]. The authors of [9] suggested the time-spectrum resource partitions in advance to accommodate various connection requests better according to the different partitions. Due to the randomness and uncertainty of connection requests, connections that requests a large number of slots may face difficulties to be accommodated over the small size as the traffic volume increases. Hence, how to measure the fragmentation resources of the network effectively and then take measures will be the most important solution [10]–[12].

Note that with the consumption of channel bandwidth growing exponentially, single-core optical fiber transmission capacity has approached its physical limit [13]; meanwhile, the single resources in frequency domain may be unable to serve the more connection requests. To achieve higher transmission capacity, SDM-EONs with 3D resources such as frequency, time, and space domain arise at the historic moment based on multi-core fiber (MCF), which are considered to be an effective solution [14]–[16] in the future. In SDM-EONs based on MCF, space dimension with core resources is introduced. First, the RSA is extended to RCSA, i.e., planning route, allocating core, and spectrum resources for arrived connections [17]. Then, on the top of the inherent fragmentation problem, the inter-core crosstalk (IC-XT) problem is also introduced. The IC-XT causes physical impairment to signal when the same FSs of adjacent cores are utilized, affecting the transmission of connection requests [18]. Therefore, to make the most of the capacity advantage of SDM-EONs, we need solve the fragmentation problem effectively based on the consideration of IC-XT.

To achieve a lower blocking probability, the authors in [19] proposed a hierarchical-graph-assisted network resource model for the first time and an RCSA algorithm that the seven-core fiber was divided into three layers according to the number of adjacent cores, addressing the dual challenges of IC-XT and spectrum fragmentation. Nevertheless, during the resource allocation process, it was translated into a two-dimensional (2D) rectangular packing. This paper provided a new way to avoid IC-XT, but the measurement of 3D resources in the network has some limitations. Only a few papers have so far focused on fragmentation metrics.

Thus, we concentrate on the spectrum allocation process of connection requests from the effective measurement of 3D resources. We first account for free SBs' accommodation capability for the connection requests in frequency domain, and select the SB with minimal occupied resources to reduce fragmentation. Then, the remaining time of free SBs in time domain is considered, striving to find a SB based on the alignment of the surrounding connections remaining time for the requests (i.e., minimal future fragmentation). Finally, we evaluate resource occupation for the existing connections to realize maximum free resource reservation on the core in space domain. Based on these, a combined 3D

fragmentation metric is provided, called the “available spatial fragmentation rate” (ASFR). This is a new way to measure the 3D fragmentation of SDM-EONs with frequency-domain spectrum resources, time-domain request remaining time, and space-domain core resources. Besides, we propose a fragmentation-minimizing scheme (ASFR-RCSA) by calculating ASFR, allocating the optimal fragmented spectrum slots for the incoming connection requests to leave more free resources for future requests. The results show that the proposed scheme can measure fragmentation better, reducing the generation of fragmentation, improving obviously in the block rate, spectrum utilization, and fragmentation rate.

The rest of this paper is organized as follows. Related work on the fragmentation problem is presented in Section II. In Section III, we show the system model in SDM-EONs. Section IV describes the 3D measurements of spectrum fragmentation in detail. In Section V, we propose the RCSA scheme based on ASFR. Then, we evaluate the performance of the proposed scheme in Section VI. Finally, Section VII concludes the paper.

## II. RELATED WORKS

Recently, various studies have been reported on the measure of the fragmentation resources. A metric was showed in [10] to quantify the consecutiveness of the common available spectrum slots among relevant fibers. The authors in [11] investigated the RSA approach based on the relationship between spectrum blocks' (SBs') accommodation capability and traffic bandwidth distribution. Reference [12] proposed two metrics including cut-based and alignment to evaluate fragmentation, then the authors of [20] defined the “wasted-unusable-free ratio” fragmentation metric based on a certain path for connection requests. However, the abovementioned works do not evaluate the effect of the time dimension, which may lead to future fragmentation. In other words, fragmentation management is only for a short time; once the requests left, network resources would become disorder again.

In [21], spectrum assignment algorithms were studied in the time-spectral domain that avoid forming future fragmentation. Reference [22] proposed a new fragmentation metric in the time domain, and a combined spectral-time metric is proposed. Based on this, the authors of [23] offered the first fragmentation-aware algorithm considering the neighbor link's spectrum resources in the 3D environment, i.e., temporal, spectral, and spatial domains. In [24], a new time variance metric was designed for measuring the busy holding time of adjacent frequency slots (FSs), and a model with the minimal time variance in the spectrum-space auxiliary graph was further established. The above metrics provide us with a comprehensive 3D resource measurement idea, and the proposed method reduces the generation of fragmentation resources accommodating more business requests.

To suppress the spectrum fragmentation of SDM-EONs, a spectrum defragmentation strategy triggered by the spectrum compactness was discussed in [25]. The strategy firstly used the spectrum compactness in the frequency domain to

measure the spectrum state of the network, and then decided whether to perform the defragmentation. Based on this, reference [13] defined a new space-time spectrum compactness measurement and reconfigured network spectrum fragmentation resources through a more accurate method. In addition of defragmentation, the authors of [26] considered both the fragmentation state of spectrum on the path and the closeness between the network nodes to avoid excessive use of the bottleneck path, thus reducing the separation of FSs. Reference [27] used several criteria, such as core fragmentation rate, to choose the best path and SB, using classifications for cores in MCF and push each connection in its related core, which improves the spectrum utilization. Reference [28] suggested a service provisioning mechanism by mining the potential association rules between the crosstalk and spectrum fragmentations.

Reference [29] introduced a path-based fragmentation measurement method, called Fragmentation Measure Metric (FMM). Then, the proposed RCSA scheme (FMM-RCSA) selected the path with a large degree of fragmentation first for the connection requests by calculating FMM, avoiding the generation of fragmentation. However, this measurement only considered the current state of spectrum occupation in the network, not future fragmentation caused by the remaining time and not occupied core resources. At the same time, it neglects fragmentation's formation on the phase of core and spectrum allocation. Limitations show in solving the fragmentation problem. Therefore, this paper tackles how to enhance spectrum utilization considering spectrum occupation and remaining time of the current requests from the three dimension.

In general, effectively measuring the fragmented resources of the network and putting forward the corresponding fragmentation-aware methods are an important means of resource optimization. Some achievements have been made in the study of fragmentation in EONs. Many articles have comprehensively measured the fragmentation resources in a multi-dimensional way, which provides us with a new perspective to figure out this problem. However, when the core resources are introduced in SDM-EONs based on MCF, people pay more attention to the IC-XT problem. The fragmentation is not reconsidered from frequency, time and space domain after the introduction of a new form of resource, lacking a truly 3D way to measure it more accurately.

### III. SYSTEM DESCRIPTION

#### A. NETWORK MODEL

The SDM-EONs are modeled as a graph  $G(V, E)$  where  $V$  is the set of network nodes, and  $E$  is the set of bi-direction physical links that interconnects them. In the paper, the threshold of the IC-XT, denoted by  $XT_{\text{threshold}}$ , is considered. Each core provides lots of available spectrum divided into spectrum resources small FSs. We denote each FS base capacity in GHz as  $BC$  on the link. In our system model, the connection request with beginning time  $t_b$  and ending time  $t_e$ , bandwidth

requirement  $b$  Gigabit per second (Gbps) and demands a lightpath from node  $s$  to node  $d$  is denoted as  $R(s, d, b, t_b, t_e)$ . When a connection request  $R_i$  dynamically arrives at the network,  $R_i$  is either established or blocked with a lightpath  $P_{R_i}$  from node  $s_i$  to node  $d_i$  in the available SB  $[f_{s_i}, f_{e_i}]$  by the control plane, in which the value of the SB is  $f_i$  GHz and calculated from (1). Moreover,  $f_{s_i}$  and  $f_{e_i}$  are the index of start FS and end FS of the SB, respectively. We assume no spectrum or core converter in SDM-EONs owing to its high complexity and cost. The size of the SB for a request  $R_i$  is calculated by:

$$f_i = \lceil \frac{b_i}{BC * M} \rceil \quad (1)$$

where  $b_i$  is the bandwidth requirement of connection  $R_i$ ,  $BC$  is the FS base capacity and  $M$  is modulation level of the connection request  $R_i$ . Some notations and their definitions used in the paper are listed in Table 1.

TABLE 1. Notations and their definitions.

Notation	Definition
$G(V, E)$	the SDM-EONs network with bidirectional graph.
$V$	a set of network nodes in $G(V, E)$ .
$E$	a set of bi-direction physical links in $G(V, E)$ .
$R(s, d, b, t_b, t_e)$	a set of connections requested network with beginning time $t_b$ , ending time $t_e$ , and bandwidth requirement $b$ between node $s$ and node $d$ .
$f_r$	the number of FSs occupied by existing connection $r$ .
$f_R$	the number of FSs requested by the connection $R$ .
$L$	the links requested by the connection $R$ .
$B$	total available SBs in the core $c$ of the link $l$ .
$B_i^{c,l}$	the $i$ -th available SB in the core $c$ of the link $l$ .
$B_{\max}^{c,l}$	maximum available SB in the core $c$ of the link $l$ .
$t_{s_r}$	the value of remaining time occupied by existing connection $r$ .
$t_{s_{lr}}$	the value of remaining time of requests on the first left occupied FS of the $B_i^{c,l}$ .
$t_{s_{rr}}$	the value of remaining time of requests on the first right occupied FS of the $B_i^{c,l}$ .
$t_{s_R}$	the value of remaining time requested by the connection $R$ .
$ASFR_c(l^c)$	frequency-domain weight of the link $l$ in the core $c$ .
$ASFR_t(B_i^{c,l})$	time-domain weight of the SB $B_i^{c,l}$ in the core $c$ of the link $l$ .
$ASFR_{sp}(c^l)$	space-domain weight of the core $c$ on the link $l$ .
$XT_i$	the IC-XT of the $i$ -th available SB for the connection request $R$ .
$XT_{\text{threshold}}$	the threshold of the IC-XT.

#### B. CROSSTALK MODEL

IC-XT is a key physical constraint in SDM-EONs, which can severely affect the the transmission of connection requests. To reduce IC-XT and achieve dense core arrangement, a trench-assisted MCF was proposed in [30]. The seven-core MCF model is also used in this paper. In addition, we make

use of worst-case IC-XT estimation to ensure acceptable IC-XT levels in the network, which assumes that all cores adjacent to a specific core are occupied along the entire path for any candidate path [31]. Then, we consider using (3) to calculate the mean crosstalk of a MCF. In (2),  $h$  denotes the mean increase in crosstalk per unit length, and  $k, r$  [mm],  $\beta$ , and  $\omega_{tr}$  [ $\mu\text{m}$ ] are the relevant fiber parameters, representing the coupling coefficient, bend radius, propagation constant, and core pitch, respectively [32]. In (3),  $n$  is the number of the adjacent cores and  $L$  [km] represents the fiber length.

$$h(k, \omega_{tr}) = \frac{2k^2r}{\beta\omega_{tr}} \quad (2)$$

$$XT = \frac{n - ne^{-(n+1)*2*h*L}}{1 + ne^{-(n+1)*2*h*L}} \quad (3)$$

We note that the IC-XT is mainly affected by the number of adjacent cores and the length of the fiber. Therefore, when conducting RCSA for the requests, we select the core that satisfies the IC-XT threshold, if not satisfies, the core is discarded. Meanwhile, we assume the connection requests can be transmitted successfully when the IC-XT threshold is met.

Taking connection request  $R_i$  as an example, it routed through seven-core MCF links  $e$  of lengths  $d = 1000$  [km]. In our worst-case IC-XT scenario, the central core has 6 adjacent cores (i.e.,  $n = 6$ ), while the other cores have 3 adjacent cores (i.e.,  $n = 3$ ). We assume the power-coupling coefficient of  $h = 10^{-10}$ . Therefore,  $-32.2$  [dB] and  $-35.2$  [dB] would correspond to central core and other cores by using (3), respectively.

#### IV. 3D FRAGMENTATION METRIC-AVAILABLE SPATIAL FRAGMENTATION RATE

In this section, we make a detailed introduction to the 3D fragmentation metric of SDM-EONs in the frequency, time, and space domains. To this end, we first extend the existing approaches for measuring fragmentation in the frequency domain. Then, we show a new fragmentation metric in the time domain. Specially, we measure the occupancy of resources to minimize fragmentation in the space domain, and a 3D metric combined with them is proposed to achieve the goal of solving the fragmentation problem.

First, we show the 3D resource pool of resource occupancy for a certain link under the network in Fig. 1. Here, the three axes represent the spectrum, time, and core resources, respectively. The spectrum and time resources on each core are divided into small FSs and remaining time slots (RTSs), respectively. The resource occupancy of color represents a corresponding request. For each connection request  $R_i(s, d, b, t_b, t_e)$ , the remaining time  $t_i$  is calculated by:

$$t_i = t_{e_i} - t \quad (4)$$

where  $t_{e_i}$  is the ending time, and  $t$  is the current running time of the network. The number of the RTSs  $ts_i$  can be

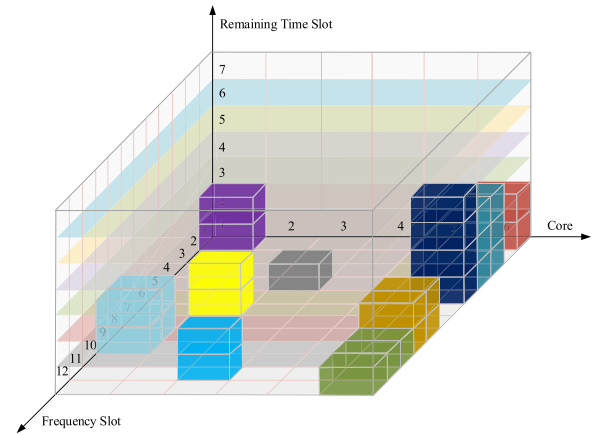


FIGURE 1. 3D resource pool of resource occupancy in SDM-EONs.

obtained [19]:

$$ts_i = \lceil \frac{t_i}{\tau} \rceil \quad (5)$$

where  $\tau$  is the time slot base capacity. Based on this, we can focus on 3D fragmentation metric-ASFR now.

#### A. AVAILABLE SPATIAL FRAGMENTATION RATE IN FREQUENCY DOMAIN

The fragmentation metric of the frequency domain has been covered in many articles. The authors of [33] defined a classic metric as the ratio between the size of maximal available SB and the total free SBs on the link. However, this metric does not reflect whether the available SBs of the fragmented link can accommodate the requested bandwidth (i.e., whether the block is fragmentation for the request). In other words, the formation of fragmentation is necessarily related to the bandwidth request. For example, the SB of three FSs is regarded to be fragmentation if the number of FSs requested by the connection is larger than three.

Therefore, we consider that the ratio of the difference between the  $B_{max}^{c,l}$  and  $f_R$  required by the connection  $R$ , and the total free slots as the frequency weight of the link  $l$  in the core  $c$ . The frequency-domain weight  $ASFR_s(l^c)$  is calculated by (6), which means the extent to which the fragmentation resources can accommodate the requests at the present.

$$ASFR_s(l^c) = \frac{B_{max}^{c,l} - f_R}{\sum_{i=1}^K B_i^{c,l}} \quad (6)$$

#### B. AVAILABLE SPATIAL FRAGMENTATION RATE IN TIME DOMAIN

For the fragmentation problem of a dynamic network, we consider the measurement of the current fragmentation in the frequency domain, which may have a certain mitigation effect for a short time. However, once connections terminate after their remaining lifetimes, this method will fail with the departure of connections in the network, which may lead to the emergence of more fragmentation. Therefore, it is essential to introduce the time domain, which affects future



fragmentation formation. Based on this, for available SB  $B_i^{c,l}$  in the core  $c$  of the link  $l$ , we consider its time-domain weight  $ASFR_t(B_i^{c,l})$  as the percentage of the absolute value of the difference between the remaining time of  $B_i^{c,l}$  (i.e., average RTSs of two requests occupied the first left and first right FS of the  $B_i^{c,l}$ ) and the RTSs requested by the connection  $R$ :

$$ASFR_t(B_i^{c,l}) = \frac{| \frac{ts_{lr} + ts_{rr}}{2} - ts_R |}{100} \quad (7)$$

where  $ts_{lr}$  and  $ts_{rr}$  represent the RTSs of left and right requests, respectively. For example, there are two free SBs on the core 6 in Fig.1, and the remaining time of the first free SB (i.e., slot 2) is 2.5 (i.e.,  $\frac{2+3}{2}$ ).

The smaller the value of  $ASFR_t(B_i^{c,l})$  is, the closer the remaining time of  $B_i^{c,l}$  is to the connection request  $R$ . That is, then, the request is gone together with the left and right requests at the same time, which will make more room for future requests and reduce the generation of fragmentation.

### C. AVAILABLE SPATIAL FRAGMENTATION RATE IN SPACE DOMAIN

Core resources are introduced in SDM-EONs based on MCF, extending the original network resources to three dimension. To cope with this new resources, we concentrate on the resource occupancy of all existing requests in the cores. We define the space-domain weight  $ASFR_{sp}(c^l)$  of the core  $c$  on the link  $l$ , as the sum of the product of FSs and RTSs occupied by each requests  $r$ , as shown in (8):

$$ASFR_{sp}(c^l) = \sum_{r \in R} f_r * ts_r \quad (8)$$

We regard the five requests in the core 6 of this link in Fig. 1 as a simple example to illustrate this weight. Here, the space-domain weight of this link is 19 (i.e.,  $1 * 2 + 2 * 3 + 1 * 4 + 2 * 2 + 3 * 1$ ). The larger the value of  $ASFR_{sp}(c^l)$ , the larger the occupied resources in the core  $c$ .

### D. 3D FRAGMENTATION METRIC WITH ASFR

Given the definitions of three weight above, we can propose the true 3D fragmentation metric-ASFR now. The ASFR of each available SB  $B_i$  in all cores of the link  $l$  is calculated by (9):

$$ASFR(B_i^{c,l}) = \sum_{l \in L} ASFR_s(l^c) * ASFR_t(B_i^{c,l}) * \frac{1}{ASFR_{sp}(c^l)} \quad (9)$$

where  $L$  is the links requested by the connection  $R$ . More in detail, the metric is composed of three parts. The first two parts are the frequency-domain and time-domain weights respectively, which represent the consideration of existing and future fragmentation at the same time, in order to find the optimal fragmented SB for allocating. The last part is the reciprocal of the space-domain weight in the core resource; that is to say, the larger the traffic load carried in the core, the smaller the value. On the whole, the smaller the

non-negative value of  $ASFR(B_i^{c,l})$  is, the closer the use of  $B_i^{c,l}$  is to the utilization of network fragmentation.

Consider a simple example in Fig. 1 to illustrate  $ASFR$ . We assume a connection  $R$  with a FS and three RTSs requests the link  $l$ . As can be seen, there are two available SBs ( $B_1^{6,l}, B_2^{6,l}$ ) on the core 6, and the calculation process of  $ASFR(B_1^{6,l})$  is as follows:  $ASFR_{sp}(6^l) = 19$ ,  $ASFR_s(6^l) = \frac{2-1}{3} = 0.333$ ,  $ASFR_t(B_1^{6,l}) = \frac{| \frac{2+3}{2} - 3 |}{100} = 0.005$ , hence,  $ASFR(B_1^{6,l}) = \frac{1}{19} * 0.333 * 0.005 = 8.77 * 10^{-5}$ .

## V. FRAGMENTATION-MINIMIZING RCSA SCHEME-ASFR-BASED RCSA

This paper describes an RCSA scheme based on ASFR. The scheme takes into account the fragmented resources of frequency, time, and space domain in the process of resource allocation for connections to achieve fragmentation minimizing in SDM-EONs. For each connection request, it chooses the available SB with a minimum value of ASFR, improving the utilization of spectrum resources. The SB is from spectrum resources with minimal occupied resources, and core resources with maximum free resource reservation. Moreover, the block based on the alignment of the surrounding connections remaining time for the requests minimizes future fragmentation. At the same time, the IC-XT is considered. The spectrum resources satisfying the IC-XT threshold are selected for the requests, which guarantees the connection requests can be transmitted successfully.

The procedure of spectrum allocation for each lightpath request in our proposed scheme is given in Algorithm 1. When a connection request  $R(s, d, b, t_b, t_e)$  arrives, we first plan  $k$  shortest paths as  $P$  with KSP algorithm for it (step 1). Next, the number of FSs and RTSs requested by connection  $R$  on the path  $P_j$  are computed using (1) and (5) respectively (steps 2-3). Then, total available SBs and resources occupied by connections in the all cores are searched, if SBs are found, the IC-XT is calculated by using (3) in turn (steps 4-8). Next, if their  $XT_i$  is less than the  $XT_{threshold}$ , their  $ASFR_i$  is calculated by using (9) (steps 9-14). Finally, the block with the minimum value of  $ASFR$  is allocated for the request  $R$  (step 15). Otherwise, the connection request  $R$  is blocked after total paths are searched (steps 16-21).

The computational complexity of the scheme is determined by the number of available SBs, occupied resources in the cores and planned path. The time complexity to search available SBs for the connection requests or occupied resources is  $|C| |S| / 2$ , where  $|C|$  and  $|S|$  are the total number of FSs in each core and the total number of core in the network, respectively. The time complexity to plan paths for each lightpath request is  $O(kE \log V)$  (i.e.,  $V$  and  $E$  are the number of nodes and the number of links between nodes, respectively). Thus, the time complexity of Algorithm 1 is  $O(kE \log V |C| |S|)$ .

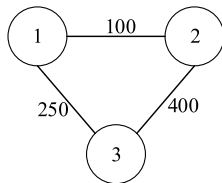
The proposed scheme is explained with an example. We suppose a simple network topology with three nodes and three links is shown in Fig. 2, The number on the link is the distance between the nodes. There are nine lightpath requests

**Algorithm 1** ASFR-Based RCSA

**input:** Arriving connection request  $R(s, d, b, t_b, t_e)$ .

**output:** Spectrum allocation.

- 1: Plan  $k$  shortest paths as  $P$  with KSP algorithm for the connection request  $R$ .
- 2: **for** path  $P_j$  from  $j = 1$  to  $j = k$  **do**
- 3:     Compute the number of FSs and RTSs requested by connection  $R$  using (1) and (5) respectively.
- 4:     Search total available SBs as  $B$  and resources occupied by connections as  $r$  in all cores.
- 5:     **if** available block can be found in  $B$  **then**
- 6:         Record the number  $n$  of available blocks.
- 7:         **for** available block  $B_i$  from  $i = 1$  to  $i = n$  **do**
- 8:             Calculate  $XT_i$  using (3).
- 9:             **if**  $XT_i < XT_{\text{threshold}}$  **then**
- 10:                 Calculate its  $ASFR_i$  using (9).
- 11:             **else**
- 12:                 Continue.
- 13:             **end if**
- 14:         **end for**
- 15:         Select the SB with the minimum of  $ASFR$  to allocate it for the connection request  $R$ .
- 16:     **else**
- 17:         **if**  $j == k$  **then**
- 18:             Reject connection request  $R$ .
- 19:         **end if**
- 20:     **end if**
- 21: **end for**



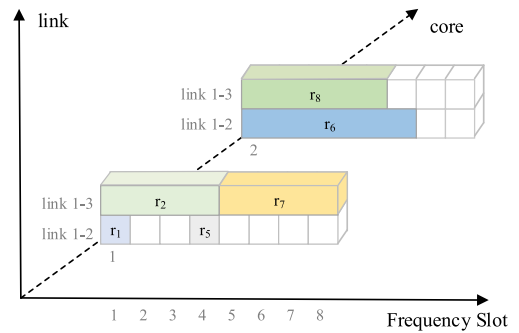
**FIGURE 2.** A simple network topology with three nodes.

for spectrum allocation considered, which are summarized in Table 2. The FMM-RCSA and ASFR-RCSA schemes are compared by calculating FMM and ASFR for each connection request, respectively. The values for both are also shown in Table 2.

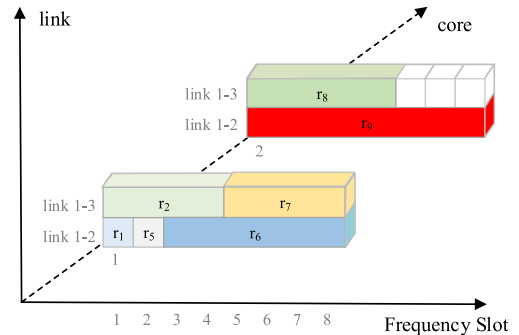
Assuming that the number of cores in the network is two, a time slot base capacity  $\tau$  is 1 [s], and each link contains eight FSs. The three axes represent the spectrum, link, and core resources respectively (to simplify of expression, the time domain is considered but not represented in the 3D resource pool). With the setup and departure of lightpath requests, we can see from Fig. 3 at 9 [s]: spectrum allocation of FMM-RCSA scheme is relatively confused, and the lightpath request  $r_9$  with the source node 1 and destination node 2 is blocked due to the shortage of available spectrum resources on the link 1-2. However, our proposed scheme can allocate resources for it successfully. This is because we take into

**TABLE 2.** Summary of connection request demands.

Light-path Request	Source node	Destination node	Number of required FSs	Beginning time [s]	Ending time [s]	FMM	ASFR
$r_1$	1	2	1	1	11	0.01	0
$r_2$	1	3	4	2	12	0.01	0
$r_3$	2	3	1	3	6	0.00875	0.00138
$r_4$	1	2	2	4	6	0.0125	0.00019
$r_5$	1	2	1	5	14	0.0125	0.00306
$r_6$	1	2	6	6	10	0.01	0
$r_7$	1	3	4	7	12	0.005	0
$r_8$	1	3	5	8	13	0.01	0
$r_9$	1	2	8	9	10	<b>block</b>	0



(a)



(b)

**FIGURE 3.** Comparison of spectrum allocation when network runs to 9 [s] using (a) FMM-RCSA and (b) ASFR-RCSA schemes.

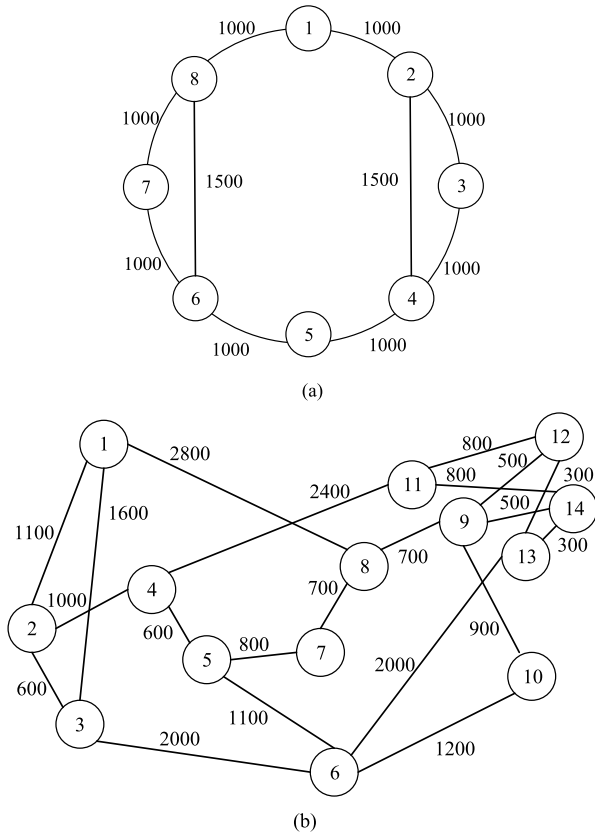
account the existing fragmentation, the remaining time of SBs, and the choice of the core, truly achieving the measurement and avoidance of spatial fragmentation by using 3D metric. Our proposed scheme addresses the fragmentation problem in SDM-EONs more comprehensively.

**VI. SIMULATION SETUP AND RESULTS**

In this section, we evaluate the performance of our ASFR-RCSA and FMM-RCSA in terms of blocking probability, spectrum utilization, and fragmentation rate. In two algorithms, a  $k$ -shortest path routing strategy, with  $k = 3$ , is used. We set up the experiments for 8 nodes with 10 bi-direction physical links of Ring Network [34], and 14 nodes with 21 bi-direction physical links of National Science Foundation Network (NSFNET) [35], [36], as shown in Fig. 4.

**TABLE 3.** The parameters used to determine transmission reach, capacity per FS, and IC-XT thresholds for each modulation formats.

Modulation formats	Transmission reach [km]	Capacity per FS [GHz]	IC-XT thresholds [dB]
DP-BPSK	4000	12.5	-14
DP-QPSK	2000	25	-18.5
DP-8QAM	1000	37.5	-21
DP-16QAM	500	50	-25



**FIGURE 4.** Physical topology of (a) Ring network and (b) NSFNET with optical fiber link length in kilometers.

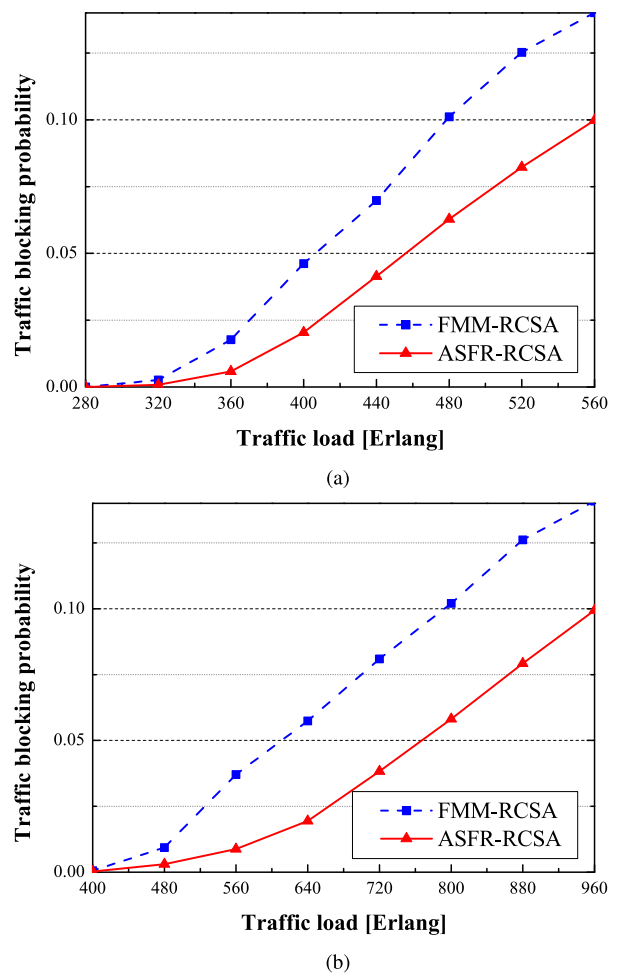
In addition, we consider that there are 358 FSs of 12.5 GHz in each core of links [28], [37]. Each Link of the network includes MCF with seven enabled cores, and the bandwidth requests are uniformly distributed between 50 GHz and 400 GHz [26]. Four modulation techniques are considered in two algorithms, namely, BPSK, QPSK, 8-QAM, and 16-QAM. The parameters used to determine transmission reach, capacity per FS, and thresholds of IC-XT for each modulation format are shown in Table 3 [38]. We assume the guardband of two FSs to avoid interference effects between adjacent optical lightpaths [39]. The worst-case IC-XT estimation is used by both schemes. And we guarantee the connection requests can be transmitted by satisfying the IC-XT thresholds.

The fiber parameters  $k, r, \beta, \omega_{tr}$  in (2) are set as  $3.16 \times 10^5$ , 55 [mm],  $4 \times 10^6$ , and 45 [ $\mu\text{m}$ ], respectively [25]. The

results are obtained from 100,000 lightpath requests, which are generated randomly among any node pairs. The arrival of lightpath requests follows Poisson process, and the holding time follows the negative exponential distribution with mean 20 [s] ( $\lambda = 1/20$ ) [27]. The confidence interval is 95%, with less than 5% error for each displayed point of diagram.

**A. BLOCKING PROBABILITY**

Fig. 5 and Fig. 6 depict the variation of blocking probability (BP). Obviously, they have the rough same performance in terms of BP in the two networks. It can be seen that the BP increases with the increase of the traffic load, because the number of lightpath requests increases per unit time. Then, when the spectrum resources occupied by each optical link become saturated, the next incoming lightpath requests will be blocked due to the shortage of available spectrum resources.



**FIGURE 5.** TBP performance comparison on FMM-RCSA scheme and ASFR-RCSA scheme evaluated in (a) Ring network and (b) NSFNET.

**1) TRAFFIC BLOCKING PROBABILITY**

Traffic blocking probability (TBP) is as a ratio of the amount of blocked traffic requests to total traffic requests.

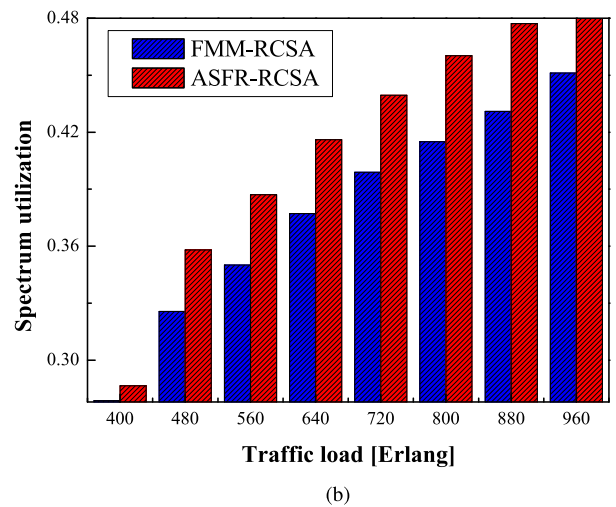
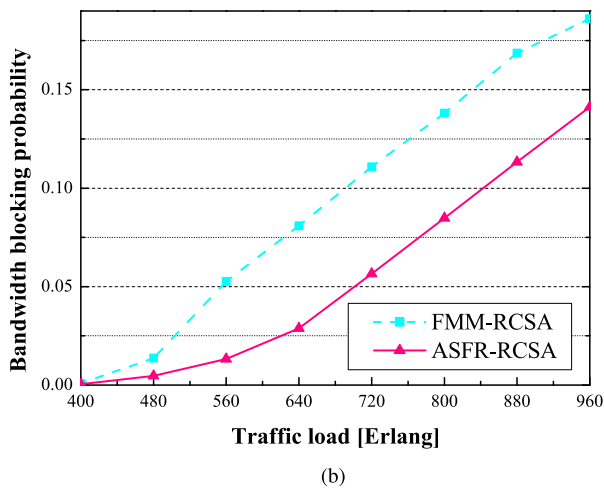
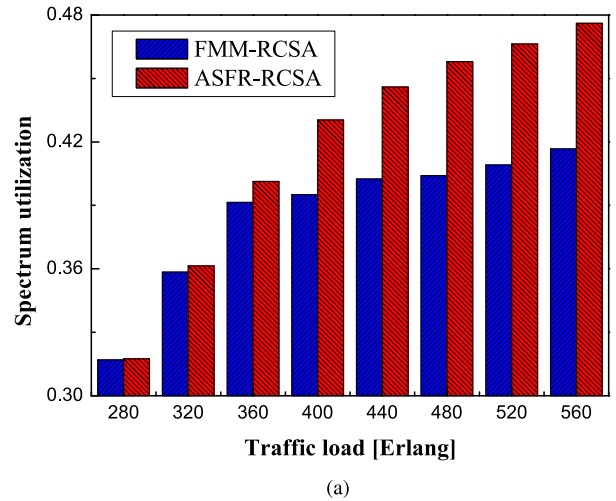
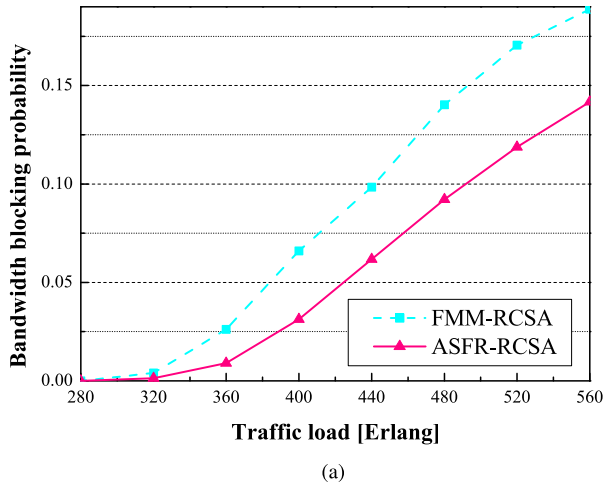


FIGURE 6. BBP performance comparison on FMM-RCSA scheme and ASFR-RCSA scheme evaluated in (a) Ring network and (b) NSFNET.

Fig.5 (a) and (b) compare the TBP of the conventional FMM-RCSA scheme and the proposed ASFR-RCSA scheme in Ring network and NSFNET, respectively. As we can see, ASFR-RCSA scheme has lower TBP than conventional scheme, which proves our scheme can carry more traffic requests. This is because it measures 3D fragmentation in SDM-EONs comprehensively using ASFR, and selects available free resources with the maximum degree of fragmentation, leaving more continuous room for future traffic requests and improving their success rate. We note from Fig.5 that TBP in NSFNET is reduced by 6% than in Ring network when the traffic load is 480 [Erlang]. This is because there are more available candidate routing paths and more allocation methods in NSFNET. In another word, the connectivity of NSFNET topology is better, and there are more opportunities to establish lightpath successfully.

2) BANDWIDTH BLOCKING PROBABILITY

Bandwidth blocking probability (BBP) is as a ratio of the blocked bandwidth to total requested bandwidth. The BBP of the ASFR-RCSA scheme is lower than conventional scheme

FIGURE 7. SU performance comparison on FMM-RCSA scheme and ASFR-RCSA scheme evaluated in (a) Ring network and (b) NSFNET.

in Fig. 6, because the harmonious operation in the spectrum and core allocation reduces the spectrum fragmentation. In particular, the proposed scheme accommodates 15% and 28% more admissible traffic volume than that using the conventional scheme when the satisfied blocking probability is considered 5% in Ring network and NSFNET, respectively. This is attributed to the fact that our fragmentation-minimizing scheme is able to create connections for each bandwidth request by planning the network resources reasonably. The fact makes the available resources in the network more continuous, satisfying traffic requests with greater bandwidth.

B. SPECTRUM UTILIZATION

Spectrum utilization (SU) is defined by [9]:

$$SU = \frac{\lambda * (FS_{S_{all}} - FS_{S_{block}})}{FS_{S_{total}} * Time} \tag{10}$$

where the holding time of total connections follows the negative exponential distribution with mean  $\lambda$ ,  $FS_{S_{all}}$  rep-



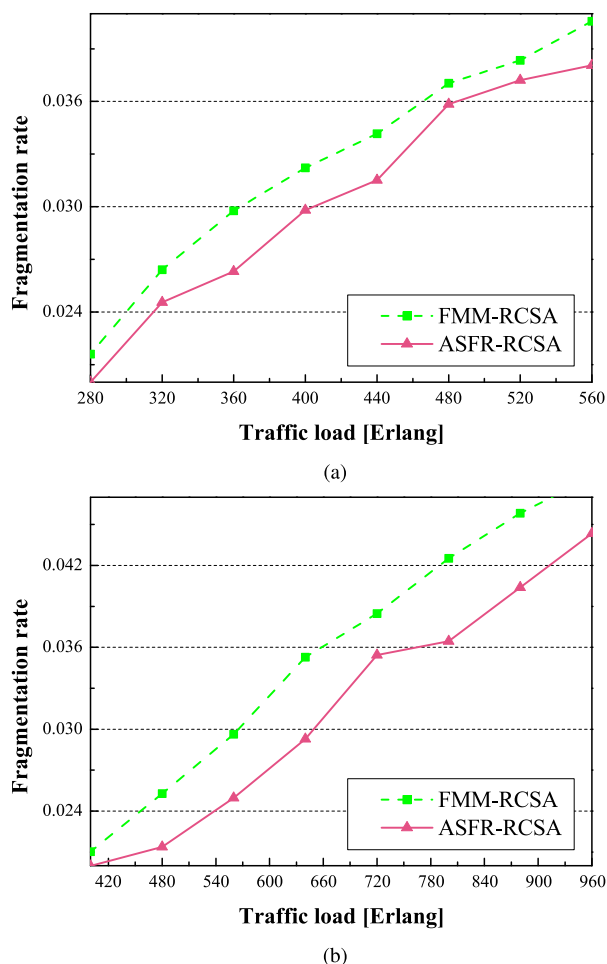


FIGURE 8. FR performance comparison on FMM-RCSA scheme and ASFR-RCSA scheme evaluated in (a) Ring network and (b) NSFNET.

resents the required spectrum resources of all connections,  $FS_{S_{block}}$  shows the required spectrum resources of all blocked connections,  $FS_{S_{total}}$  denotes total FSs in SDM-EONs, and  $Time$  represents running time of the network. By definition, SU represents the occupancy of spectrum resources for all connection requests of the network. In Fig. 7, our scheme has higher SU than the conventional scheme. There are two reasons for the high SU. On the one hand, our scheme has a lower BP, which means that it can accommodate more connections (i.e., more spectrum occupancy) in the running time of the network. On the other hand, more importantly, when allocate spectrum for each connection, we take into account 3D fragmentation of the network to find the spectrum and core resource that can accommodate and leave the largest room, which is bound to have better spectrum planning than the conventional scheme, resulting in a significant increase in spectrum occupation.

C. FRAGMENTATION RATE

Fragmentation rate (FR) is as ratio of the number of free SBs to free FSs. By definition, the FR shows the occupancy of

fragmentation resources in the network. It can be seen from Fig. 8 that the proposed ASFR-RCSA has a low FR. This is because we consider the fragmentation resources from the frequency-time-space domain when allocate spectrum for the connection. The extent to which the fragmentation resources can accommodate the connections in the frequency domain is considered to minimize fragmentation of the network. Then, the remaining time of the SB in the time domain is calculated. We select the SB that can be transmitted synchronously with the connection to minimize future fragmentation. Finally, the occupation of existing spectrum resources in the space domain is considered to realize maximum free resource reservation, improving the utilization of fragmentation resources and reducing the FR.

In summary, our scheme will have better performance than the conventional scheme in BR, PU, and FR. We make better use of the smaller fragmentation resources of the network and realize the aggregation of fragmentation by using 3D metric-ASFR, which makes the resource state more regular improving the network performance. This will be the greatest contribution to our work.

VII. CONCLUSION

In this paper, we study the issue of the complex 3D fragmentation in SDM-EONs. From the perspective of effective resource measurement, we comprehensively analyze the formation of 3D fragmentation in the frequency, time, and space domain. Based on this, we propose the ASFR, and then select the optimal fragmentation resources for the connection requests in the ASFR-RCSA. Numerical results show that our scheme has lower BP, FR, and higher SU than the traditional scheme. The benefits of our method result from we find the spectrum place with minimal occupied resources and SB based on the alignment of the surrounding connections' remaining time to minimize fragmentation. At the same time, we realize maximum free resource reservation of the core in the space domain, resulting in significantly improved network performance.

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